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# AUTONOMOUS NAVIGATION & COLLISION AVOIDANCE SYSTEM FOR THE NEARHOS UAV

**STN ATLAS – 3 SIGMA & Technical University of Crete**
**Collaboration Project**

**Presented by:**

**Prof. Kimon Valavanis**

# Report Documentation Page

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# NEARCHOS UAV SYSTEM
# OPERATIONAL - TECHNICAL CHARACTERISTICS

| | |
|---|---|
| **WING SPAN:** | 5.10m |
| **WING AREA:** | 2.95m$^2$ |
| **OVERALL LENGTH:** | 3.95m |
| **MAXIMUM TAKE-OFF-WEIGHT:** | 190kg (tricycle take off)<br>110kg (by catapult) |
| **MAXIMUM PAYLOAD:** | 51-92kg |
| **OPERATIONAL SPEED:** | 75 - 220km/h |
| **OPERATIONAL RANGE:** | 100 km |
| **FLIGHT ENDURANCE:** | 8-12 h |
| **OPERATIONAL ALTITUDE:** | 100 - 7000 m |
| **TAKE OFF:** | TRICYCLE / CATAPULT |
| **RECOVERY:** | TRICYCLE LANDING / PARACHUTE |
| **PROPULSION UNIT:** | WANKEL 38 BHP/7800 RPM |

NEARCHOS UAV SYSTEM

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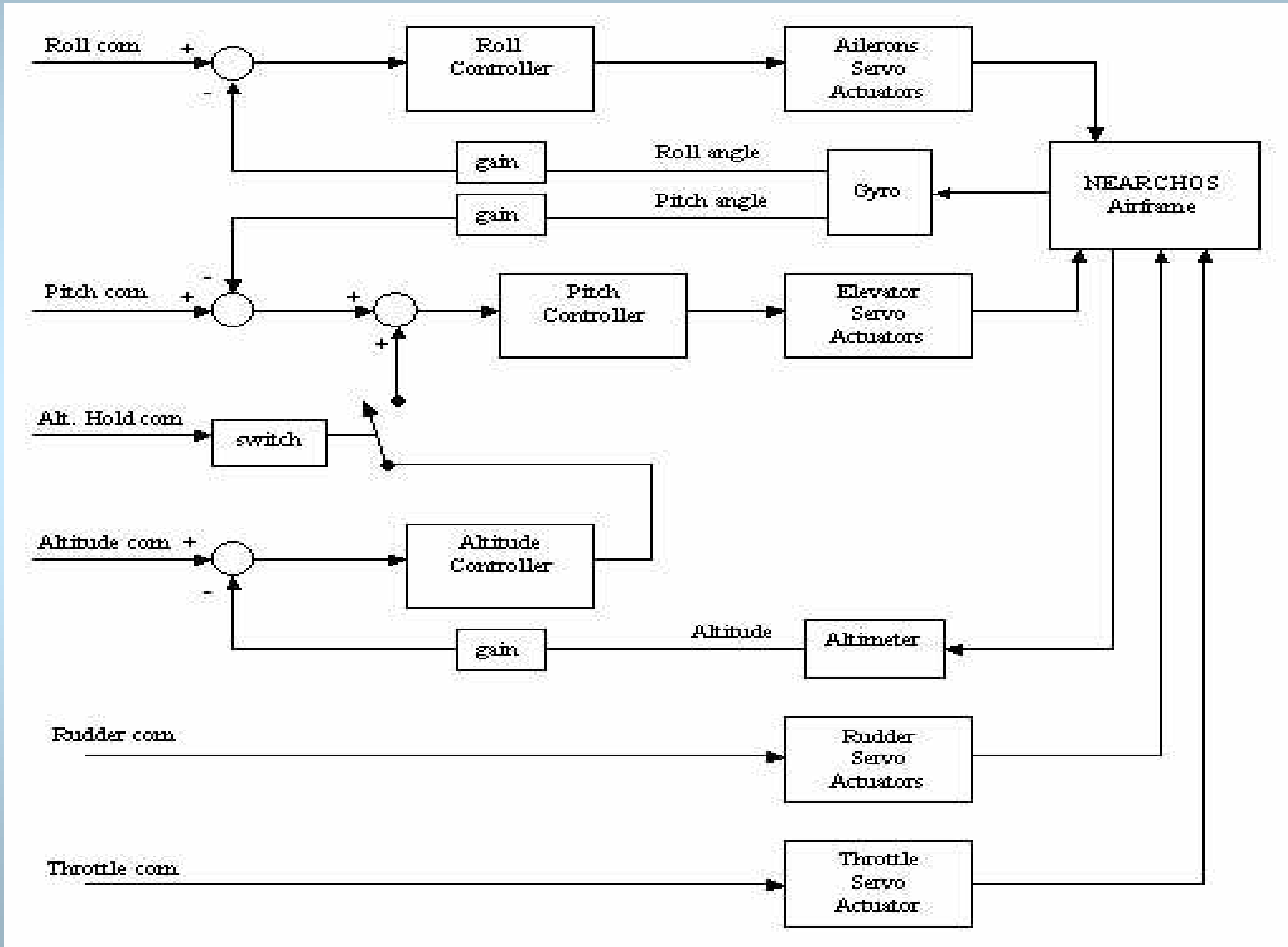
# Existing NEARCHOS Flight Control System (FCS)



# Initial NEARCHOS Flight Control System
## (commands transmitted via RF communication links)

Roll control by controlling the ailerons servo actuators.

Pitch control by controlling the elevator servo actuators.

- when altitude hold is activated, a signal proportional to the difference between commanded and actual flight altitude is added to the commanded pitch angle.

Throttle and rudder control are open loop.

Roll and pitch feedback loops help maintain stability but also result in different operation of the control sticks (control commands) compared to a general aviation aircraft, i.e.:

- a constant pitch (roll) stick deflection results in maintaining pitch (roll) attitude at the commanded level, instead of producing aircraft pitching (rolling) at a constant rate.

# Autonomous Navigation System (ANS) – Integration with the initial FCS



NO MODEL AVAILABLE - (no aerodynamic derivatives).

Neurofuzzy design procedure: offline controller parameters training using data from manually controlled flights (the controller “learns” to act like the operator)

Modular design: parallel operation of individual controller modules

Criteria: simpler controller structures – fast controller operation – ability to design/modify/replace controller modules individually

Inputs:

Gyro (roll and pitch angles) and engine RPM sensor readings
Desired altitude and airspeed (predefined flight profile data)
Heading and altitude errors (calculated on-line using predefined flight profile data together with GPS and altimeter readings)

Outputs: commands to the NEARCHOS FCS

# ANS Operation Principles



Desired flight profile - time series of waypoints in the 3-D space with desired airspeed when approaching a waypoint.

Data as ***(x, y, z, v, t)***, where ***x, y, z***: waypoint latitude, longitude, altitude, and ***v, t***: waypoint approach airspeed and time.

At a time instant, the ANS calculates the appropriate commands to the AV flight control system as a function of the deviation from the present waypoint (expressed by means of heading and altitude errors) and AV state variables.

Heading error: difference between the desired and actual AV heading (when positive, a right turn is desired). Desired heading: direction from the actual to the desired AV position in the XY-plane.

**The actual AV position and heading are provided by the GPS receiver, while the actual AV altitude is provided from the altimeter of NEARCHOS.**

# ANS Neurofuzzy Controllers Design



- Training set based on recorded manual flight data and organized as controller input-output pairs.
- Controller outputs (control commands to the NEARCHOS FCS) are directly available from recorded data.
- Preprocessing of recorded data is necessary to produce most of the controller inputs during the design procedure, since no flight profile is predefined during a manual flight.
- Assumption: the desired waypoint at time $t_0$ is defined from the flight data at time $t_0+10$ sec.
- This assumption means that flight data at time $t_0+10$ are considered as the desired data at time $t_0$. Thus, calculation of controller inputs at time $t_0$ is possible after applying the necessary preprocessing on the recorded manual flight data.
- Test data sets, used for evaluation of designed controllers, are also created in the same way from parts of recorded flights.

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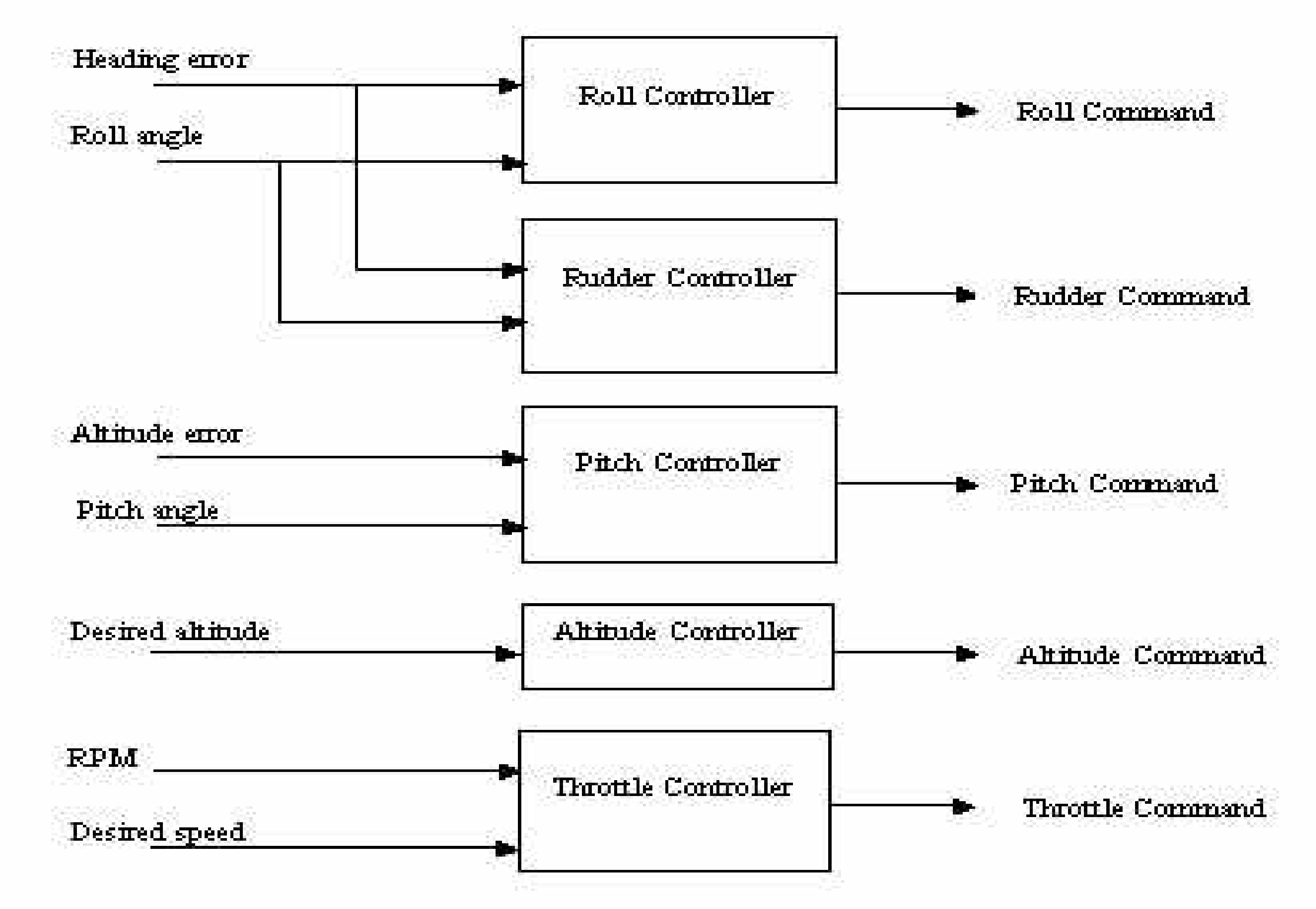
# ANS Neurofuzzy Controllers Structure (with input-output linguistic variables)

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# ANS Neurofuzzy Controllers Design



- Training and test sets for Roll and Rudder controllers (lateral control) are created using data from the same parts of recorded flights. The same holds for Pitch and Altitude controllers (longitudinal control).

- Implementation using MATLAB Fuzzy Logic Toolbox.

- Type of designed NF controllers: **zero-order Sugeno**, i.e. the rule base of each controller contains rules of the form

$$\textbf{\textit{IF x1 is A AND x2 is B THEN}}\ y_i = c_i$$

  where $c_i$: constant

- Membership Functions (MFs) of the input variables: Gaussian
- The limit values of all input variables (MFs range) are selected according to the minimum and maximum input variable values in the training set.
- AND operator: product - Defuzzification: weighted average

NOTE: First-order Sugeno type controllers were also designed, but showed inferior generalization capabilities.

# Roll Controller

- Inputs: heading error and roll angle (***headerror*** and ***phi***)
- Output: roll command to the FCS of NEARCHOS (***rollcom***)
- ***phi*** takes values in the interval [-70°, 70°]. Roll angle values outside this range are unlikely to occur in normal flight conditions of NEARCHOS
- ***headerror*** takes values in the interval [-100°, 100°]. Heading error values calculated during operation are limited to the interval [-100°, 100°] (by definition, heading error may take values in the interval [-180°, 180°]).
- Controller rule base: 35 rules of the form

If ***headerror*** is A1 and ***phi*** is A2 then ***rollcom*** is $c_i$

where A1: nb, nm, ns, Z, ps, pm, pb, A2: nb, ns, Z, ps, pb and $c_i$: constant

# Rudder Controller

- Inputs: heading error and roll angle (***headerror*** and ***phi***)
- Output: rudder command to the FCS of NEARCHOS (***ruddercom***)
- Controller rule base: 35 rules of the form

If ***headerror*** is A1 and ***phi*** is A2 then ***ruddercom*** is $c_i$

where A1: nb, nm, ns, Z, ps, pm, pb, A2: nb, ns, Z, ps, pb and $c_I$: constant

NOTE: Rudder control was not applied during the manual flights used for training data set construction. This results in keeping the rudder command practically constant for any value of the input variables

# Pitch Controller



- Inputs: altitude error and pitch angle (***alterror*** and ***theta***)
- Output: pitch command to the FCS of NEARCHOS (***pitcom***)
- ***theta*** takes values in the interval [-20$^o$, 45$^o$]. Pitch angle values outside this range are unlikely to occur in normal flight conditions of NEARCHOS
- Controller rule base: 25 rules of the form

If ***alterror*** is A1 and ***theta*** is A2 then ***pitcom*** is $c_i$

where A1: nb, ns, ps, pm, pb, A2: nb, ns, ps, pm, pb and $c_I$: constant

# Altitude Controller

- Input: desired altitude (***desalt***)
- ***desalt*** takes values in the interval [100m, 500m] (the manual flights used for training data set construction were performed in low altitude)
- Output: altitude command to the FCS of NEARCHOS (***altcom***)
- Controller rule base: 5 rules of the form

If ***desalt*** is A1 then ***altcom*** is $c_i$

where A1: low, mlow, medium, mhigh, high and $c_I$: constant

# Throttle Controller



- Inputs: engine RPM and desired airspeed (***RPM*** and ***dspeed***)
- ***dspeed*** takes values in the interval [20, 70] (m/sec)
- ***RPM*** takes values in the interval [5000, 8000]
- Output: throttle command to the FCS of NEARCHOS (***thrcom***)
- Controller rule base: 9 rules of the form

If ***RPM*** is A1 and ***dspeed*** is A2 then ***thrcom*** is $c_i$

where A1: low, med, high, A2: slow, normal, fast and $c_I$: constant

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# Real-Time Data from Test Flight

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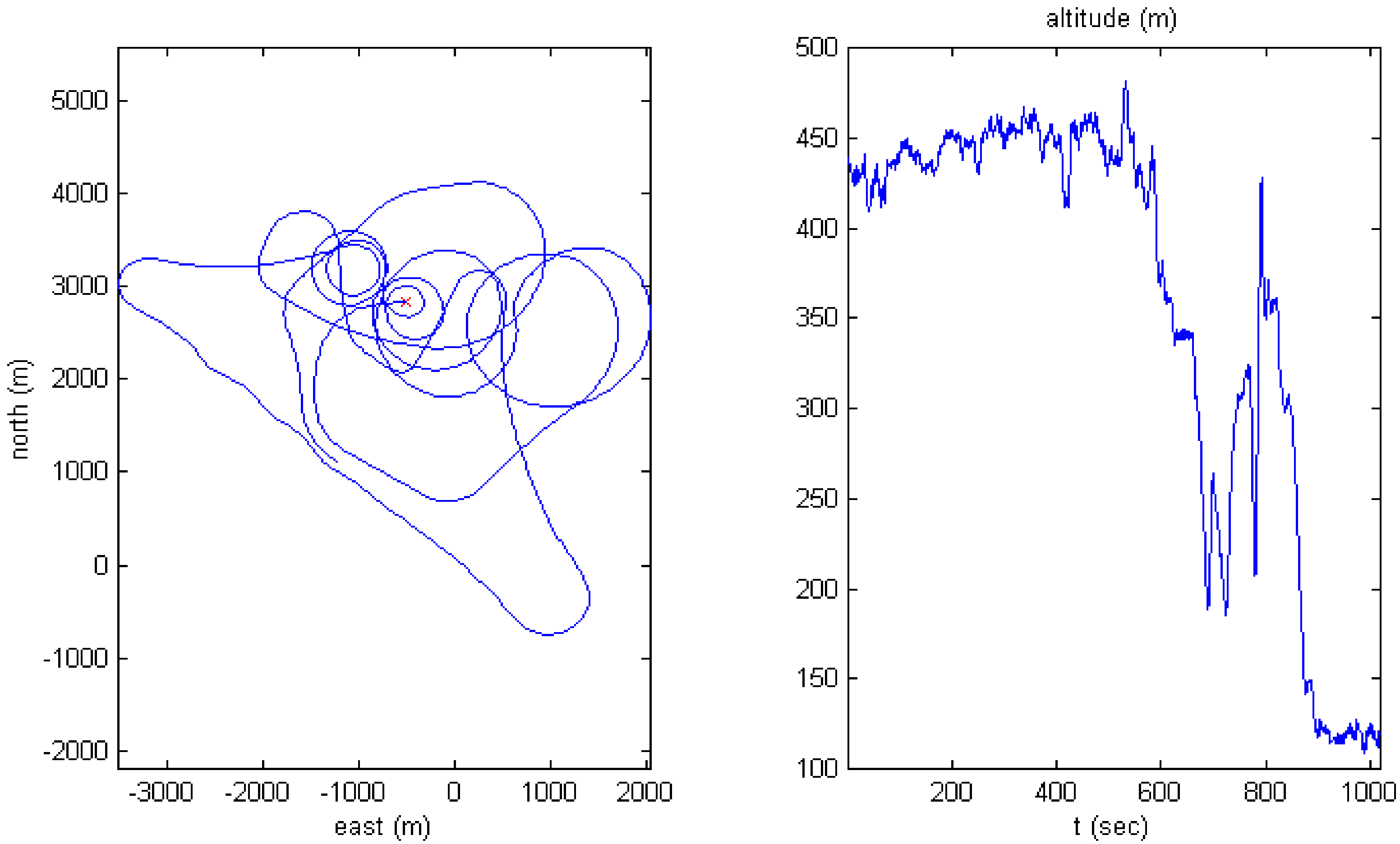
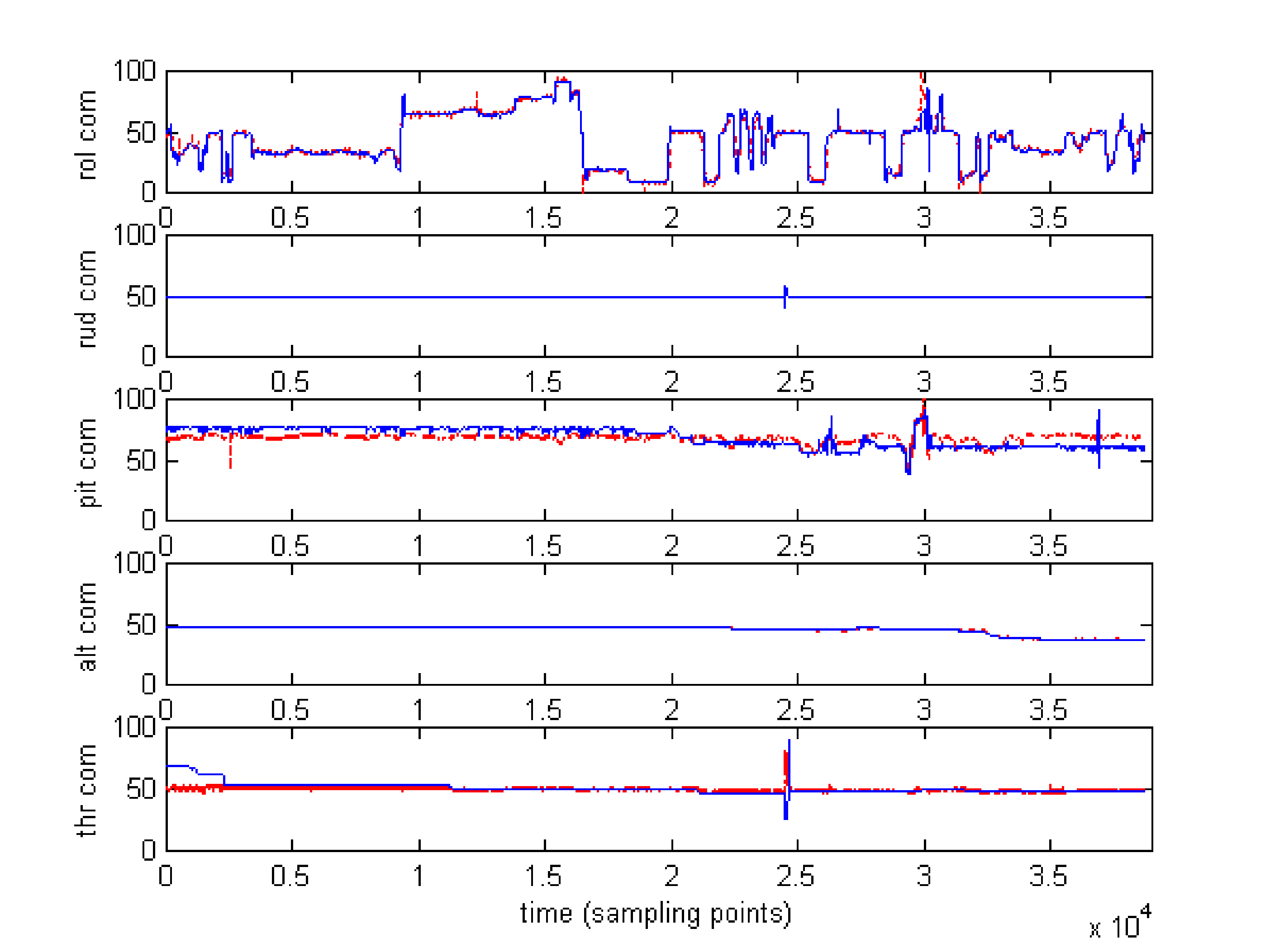


# ANS Controller Outputs – Manual Commands (Test Flight)






Manual commands: blue, controller commands: red

sampling rate is 37 samples/sec (approximately)

# Collision Avoidance System with Fuzzy Controllers



**Modular design using two FLCs**

Collision Detection module: estimates collision possibilities in four directions using preprocessed radar data (assumption: radar scans in all azimuth angles).

Course Correction module: performs corrections on the desired speed, heading error and altitude error values according to the estimated collision possibilities.

Preliminary design (controllers need tuning according to the characteristics of the collision avoidance radar to be installed)

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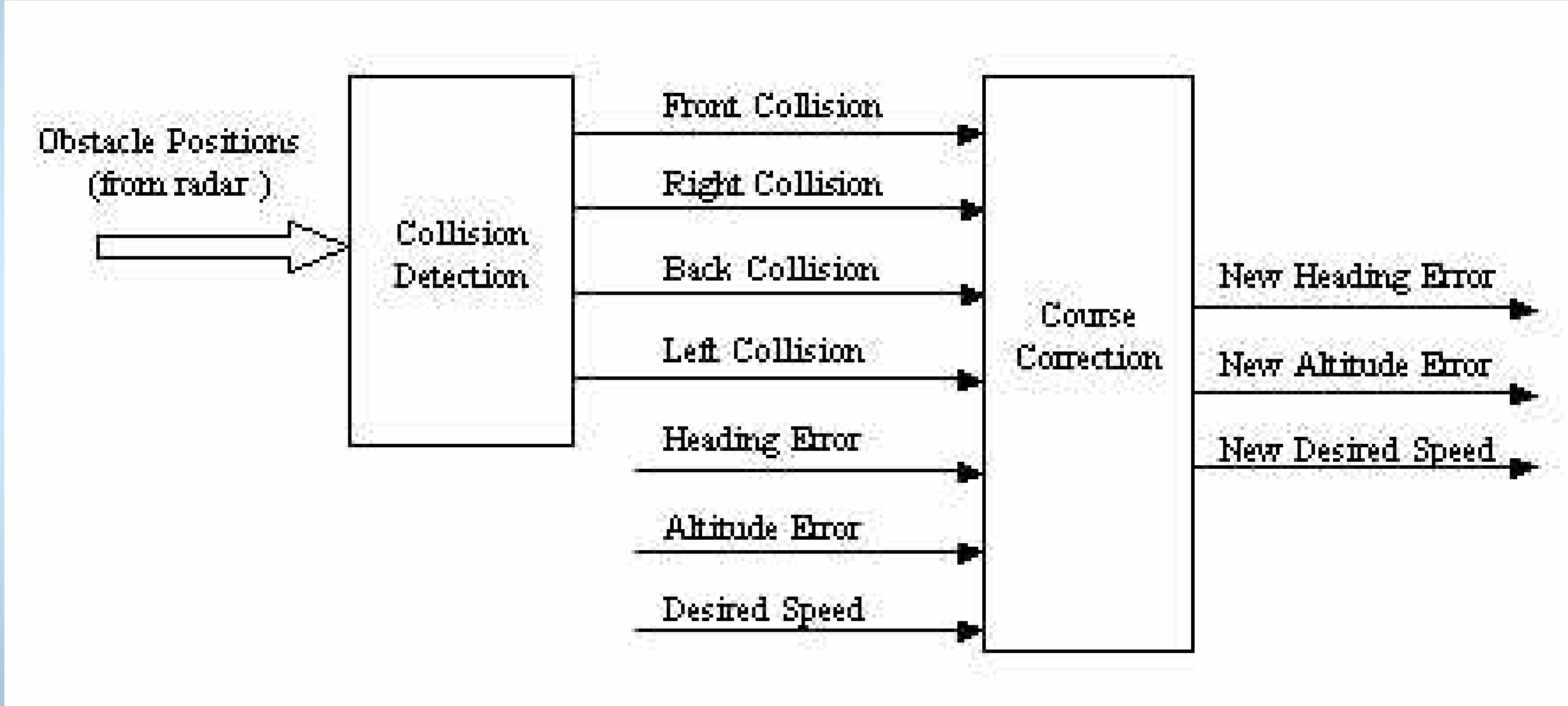
# Collision Avoidance System - FLCs structure



# Collision Detection Controller



Collision avoidance radar (Si-Tex Radar PC), performs circular scan covering the full azimuth area ($0^o$ to $360^o$) in the level of flight once every 2 seconds. Effective range 24 miles. Typical NEARCHOS speed 50 m/s ➔ set range at 12 miles.

Obstacle positions data are considered to be provided as distance - azimuth pairs. The full azimuth area is partitioned in eight sectors ($0^o$: AV heading): ***s1: [0$^o$, 45$^o$), s2: [45$^o$, 90$^o$), … , s7: [270$^o$, 315$^o$), s8: [315$^o$, 360$^o$)***

From obstacle positions detected in sector ➔ select the one with minimum distance ➔ reduce amount of data points ➔ faster operation.

Distance and azimuth of the selected obstacle positions for each sector ($s_i d$ and $s_i az$) are the inputs to the Collision Detection Controller.

If no obstacles are detected in sector i, $s_i d$ is set to the max radar scan range and $s_i az$ is set to the min azimuth of sector i.

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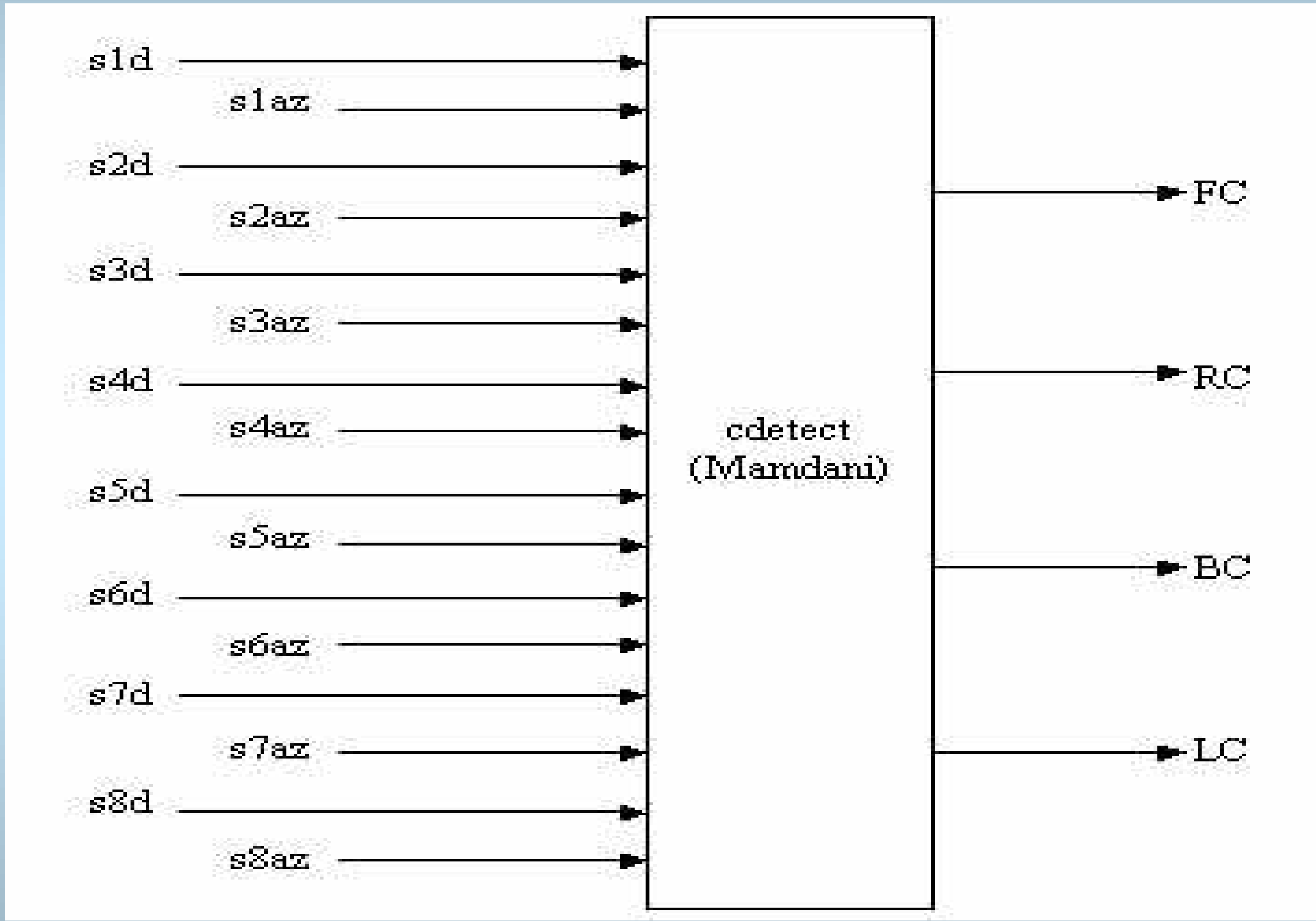
# Collision Detection Controller
# Block Diagram

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# Collision Detection Controller-Operation Principle



- Each of the controller outputs is a function of eight of the input variables, which are the distance and azimuth of the obstacles detected in the four sectors related to the output (collision possibility) in question
- Two primary and two secondary sectors are considered for each output
- Inputs corresponding to the primary sectors are dominant for output calculation. Secondary sectors are considered only when no obstacle is detected near in one or both of the two primary sectors
- Collision possibilities - azimuth sectors relationship:

| Output | Sectors | | | |
|---|---|---|---|---|
| | Primary | | Secondary | |
| FC | s1 | s8 | s2 | s7 |
| RC | s3 | s2 | s4 | s1 |
| BC | s5 | s4 | s6 | s3 |
| LC | s7 | s6 | s8 | s5 |

s1: [0$^o$, 45$^o$), s2: [45$^o$, 90$^o$), … , s7: [270$^o$, 315$^o$), s8: [315$^o$, 360$^o$)

- Obstacle azimuth is not considered when obstacle distance is far

# Collision Detection Controller - Inputs/Outputs



**Inputs:** obstacle distance and azimuth for each of the eight scan area sectors (***sid*** and ***siaz***, respectively, i = 1, 2, …, 8).

***sid*** linguistic values: close, near, far. ***sid*** membership functions range is set to the maximum radar scan distance.

Each one of the ***siaz*** linguistic variables may take two linguistic values:

| s1az | s2az | s3az | s4az | s5az | s6az | s7az | s8az |
|---|---|---|---|---|---|---|---|
| FR | FR | R | R | B | B | L | L |
| R | R | B | B | L | L | FL | FL |

**Outputs:** Front, Right, Back, Left Collision possibilities (***FC, RC, BC, LC***, respectively)

Each of the linguistic variables ***FC, RC, BC, LC*** may take three linguistic values: ***NP*** (Not Possible), ***P*** (Possible), ***H*** (High)

# Collision Detection Controller-Rule Base

- Controller type: Mamdani
- Rule base: 68 rules (17 rules for each output) of the generic form

  IF x1is A1 and x2 is A2 and … and xn is An THEN y is B
- Part of the rule base for output ***FC***:

| s1d | s1az | s8d | s8az | s2d | s2az | s7d | s7az | FC |
|---|---|---|---|---|---|---|---|---|
| close | FR | - | - | - | - | - | - | H |
| near | FR | near | FL | - | - | - | - | H |
| near | FR | far | - | - | - | - | - | P |
| near | FR | far | - | close | FR | - | - | H |
| near | FR | far | - | near | FR | near | FL | H |
| far | - | far | - | - | - | - | - | NP |
| far | - | far | - | - | - | close | FL | P |
| far | - | far | - | - | - | near | FL | P |
| far | - | far | - | close | FR | close | FL | H |

# Course Correction Controller – Inputs

Controller inputs: collision possibilities ***FC, RC, BC, LC,*** and ***headerr, alterr dspeed***.

Input range for ***headerr*** is [-180$^o$, 180$^o$] (possible heading error values) - linguistic values: nb, ns, Z, ps, pb

Input range for ***alterr*** is [-150, 250] (in meters - according to data from NEARCHOS manual flights) - linguistic values: nb, ns, ps, pm, pb

The input range for ***dspeed*** is [20, 70] (in m/sec - according to data from NEARCHOS manual flights) - linguistic values: ***slow***, ***normal***, ***fast***

# Course Correction Controller – Outputs / Operation Principle



Controller outputs fed to the Autonomous Navigation System: heading error, altitude error and desired speed, corrected according to the collision possibilities provided from the Collision Detection controller.

Linguistic values and membership functions of all three output variables are identical to those of the corresponding inputs, except that the range of variable ***cheaderr*** is [-100$^o$, 100$^o$] instead of [-180$^o$, 180$^o$] (input variable headerr). This limitation is due to the input range of the Roll and Rudder controllers of the ANS.

***cdspeed*** output is a function of ***dspeed***, ***FC*** and ***BC*** inputs

- if there is no ***BC*** possibility, no correction in ***dspeed***
- if ***BC*** possibility is low and there is no ***FC*** possibility, ***dspeed*** increases
- if ***BC*** possibility is small and ***FC*** possibility exists, no correction in ***dspeed***
- if ***BC*** possibility is high, ***dspeed*** increases, unless ***FC*** possibility is also high

# Course Correction Controller – Operation Principle



***cheaderr*** output is a function of headerr, ***FC, RC*** and ***LC*** inputs

if no collision possibility exists, no correction in ***headerr***

if ***FC*** possibility is zero or small, corrections in ***headerr*** are made only if the latter dictates a turn of the AV towards a direction where a collision is possible

if ***FC*** possibility is high, ***headerr*** is corrected so as to dictate a fast turn to the direction with the lower collision possibility

if ***FC*** possibility is high while ***LC*** and ***RC*** possibilities are zero (or equal and small), ***cheaderr*** dictates a fast turn to the same direction with ***headerr***

# Course Correction Controller – Operation Principle, cont…

***calterr*** output is a function of ***alterr***, ***FC***, ***RC*** and ***LC*** inputs

if ***FC*** possibility is zero, or ***FC*** possibility is small while both ***RC*** and ***LC*** possibilities are zero, no correction in ***alterr***

if ***FC*** possibility is small while ***FC*** and ***LC*** possibilities exist, ***alterr*** increases (altitude increase is dictated)

if ***FC*** possibility is high, ***alterr*** increases at an amount analogous to ***LC*** and ***RC*** possibilities

# Course Correction Controller – Rule Base

Controller type: Mamdani

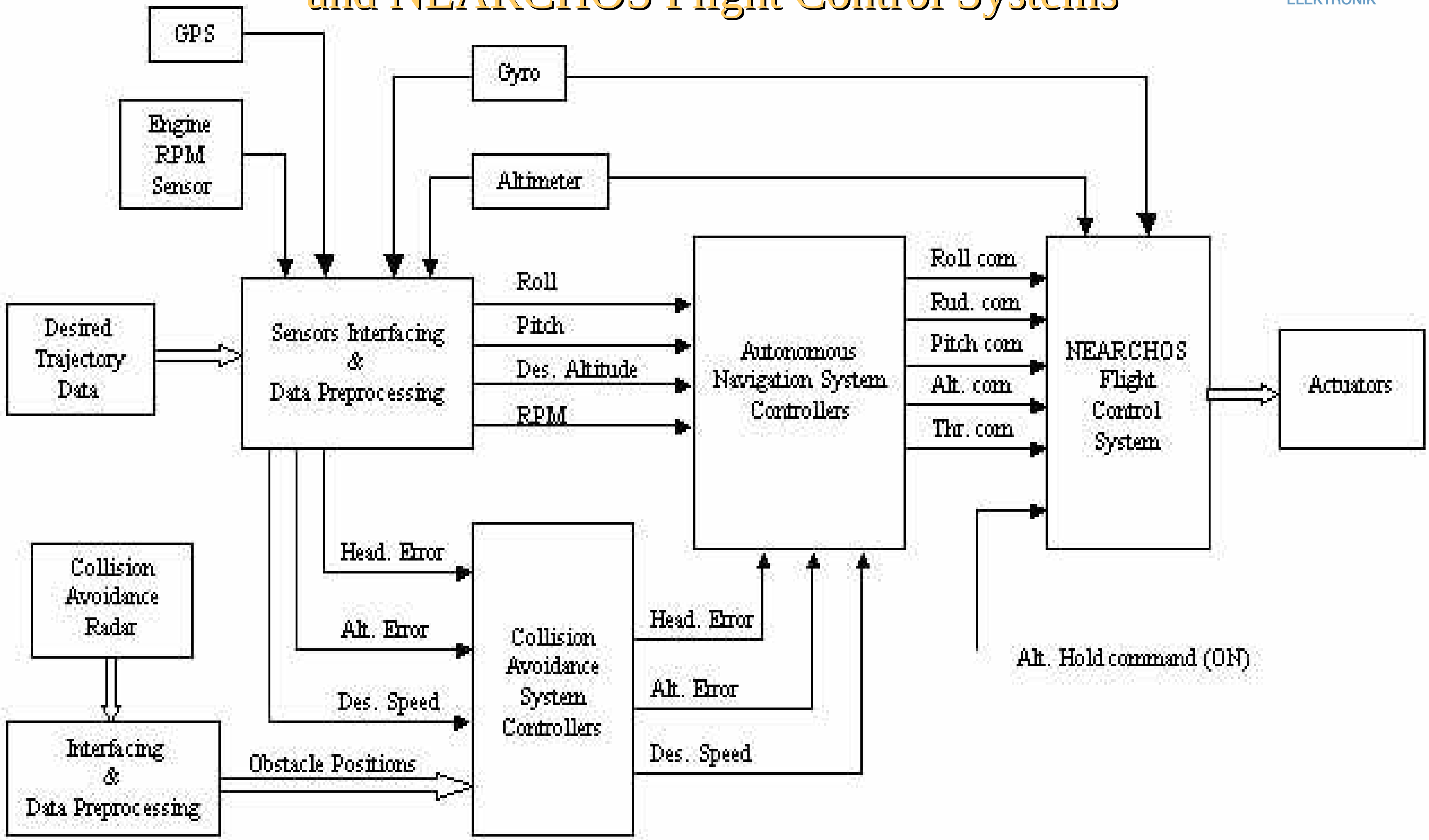
Rule base: 176 rules (71 rules for ***cheaderr***, 86 rules for ***calterr*** and 19 rules for ***cdspeed***) of the generic form

***IF x1is A1 and x2 is A2 and … and xn is An THEN y is B***

Part of the controller rule base:

| FC | RC | BC | LC | headerr | alterr | dspeed | cheaderr | calterr | cdspeed |
|---|---|---|---|---|---|---|---|---|---|
| NP | - | - | - | Z | - | - | Z | - | - |
| NP | P | - | - | pb | - | - | ps | - | - |
| P | H | - | P | pb | - | - | Z | - | - |
| H | P | - | H | - | - | - | pb | - | - |
| NP | P | - | P | - | ns | - | - | ns | - |
| P | H | - | P | - | ps | - | - | pm | - |
| H | P | - | H | - | ns | - | - | pb | - |
| NP | - | P | - | - | - | normal | - | - | fast |
| P | - | H | - | - | - | slow | - | - | normal |

# Integration of Autonomous Navigation, Collision Avoidanc and NEARCHOS Flight Control Systems



# Alternative Design (model available)

**Design and implementation of 3 FLCs:**

**guidance controller**: generates navigation commands (desired roll and pitch angles, desired speed)

inputs: heading error, position error, altitude error, airspeed

**lateral controller**: generates commands to ailerons and rudder

inputs: desired roll angle, roll angle error, roll angular velocity, yaw angular velocity

**longitudinal controller**: generates commands to elevator and engine (thrust)

inputs: pitch angle error, speed error, pitch angular velocity

(First test on a Boeing 747-100 model)

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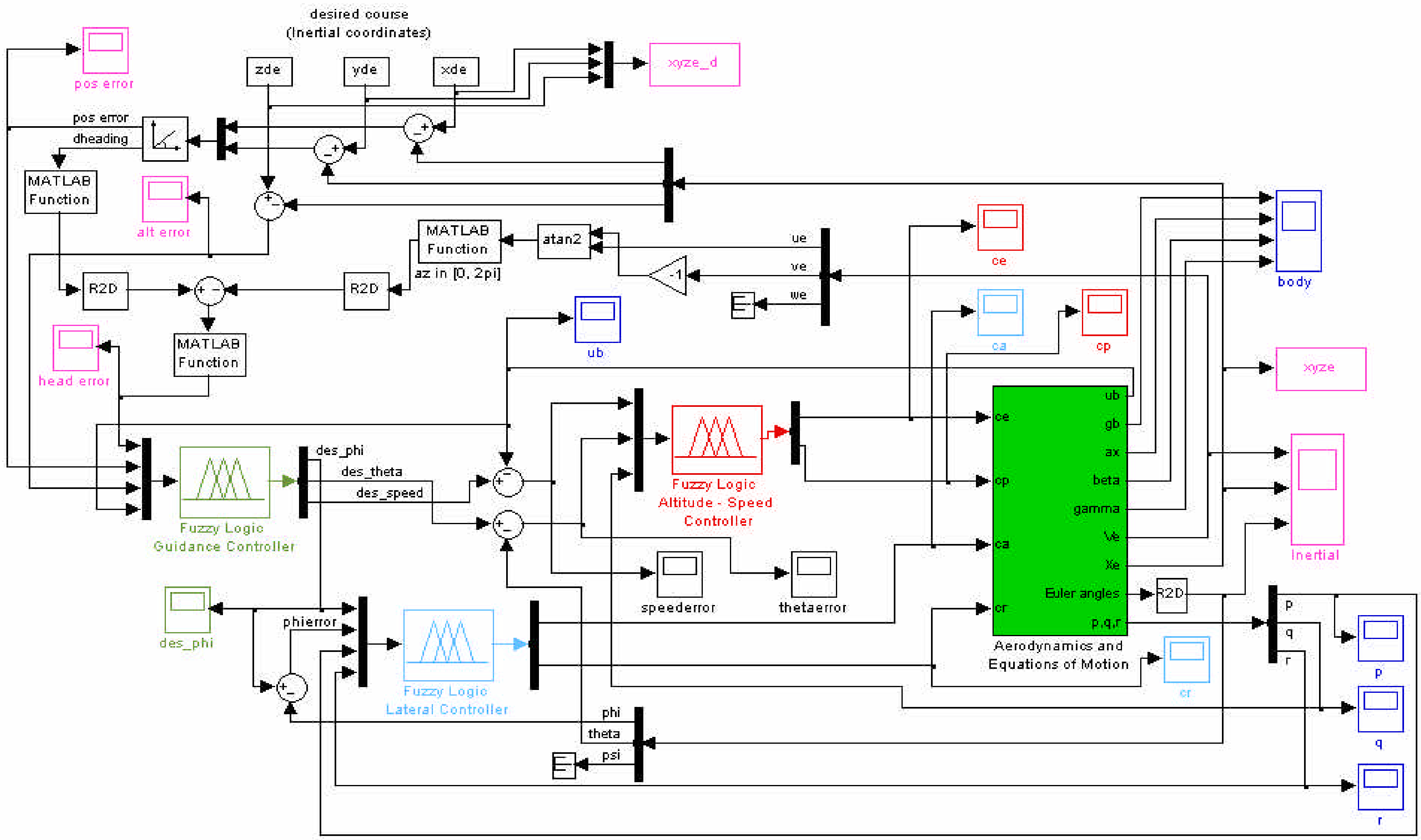
# Implemented SIMULINK Model



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